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The Elastic Anisotropy of the Whitby Mudstone Formation at Varying Water Saturations

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Summary

Mudstones are characterized by their tight matrix and are therefore of interest in various industries, including the petroleum and underground repository industry. These clay-rich rocks often show dynamic elastic anisotropy, which causes significant problems in geophysical interpretations. In addition, pore water has a significant effect on the bulk properties of mudstones. However, the degree of saturation is often not reported in the literature. This study investigates the impact of water saturation on the elastic anisotropy of the Whitby Mudstone. Four core plugs with different water saturations were deformed until failure and tested ultrasonically at effective confining pressure conditions of 25 MPa. P-wave and S-wave velocities were monitored along the symmetry axis, across the core diameter, and at ~49° to the horizontal bedding plane to calculate the full elastic tensor and subsequently the Thomsen anisotropy parameters. The degree of saturation highly affects the rock strength and static elastic properties and leads to significant changes in the elastic anisotropy parameters.

Introduction

Mudstones are the most abundant sedimentary rocks in the world, and are of interest for various industries, including the petroleum and underground repository industries. These clay-rich rocks are characterized by a tight matrix, making them relative impermeable to fluid flow. This characteristic makes a mudstone an important natural seal for conventional petroleum reservoirs and for CO_2 geo-sequestration projects.

These low permeability rocks are often highly anisotropic, causing significant issues in depth conversion in seismic exploration, or in monitoring subsurface reservoirs during injection or production. Previous studies reported velocity measurements and elastic anisotropy of mudstones (e.g., Jones and Wang 1981; Vernik and Nur 1992; Hornby 1998). However, the majority of the studies available in the literature performed their experiments on poorly preserved, unsaturated clay-rich samples without reporting the degree of water saturation.

The bulk properties of mudstones are highly dependent on the degree of saturation. Loss of pore water in these clay-rich rocks might induce damage, changing the ultrasonic velocities (e.g., Ghorbani et al. 2009) and rock strength (Vales et al., 2004; Ramos da Silva et al. 2008). Although the effect of water saturation on the mechanical properties is reported in the literature, the impact on the elastic anisotropy has attracted less attention.

This study examines the impact of water saturation on the elastic anisotropy of the Whitby Mudstone. Mudstone core plugs with different water saturations are tested ultrasonically at undrained conditions at an effective confining pressure of 25 MPa. *P*-wave and *S*-wave velocities are measured along multiple ray paths during isotropic- and anisotropic stress conditions.

Rock Material and Experimental Methods

The Mudstone samples originate from a wave-cut platform of the Whitby Mudstone Formation (WMF). This Early Jurassic Formation is used as an analogue for the Dutch Posidonia Shale Formation (PSF), which is considered as the main shale-gas prospect in the Netherlands. Mudstone blocks were collected from the same horizon in the outcrop and were stored in seawater to prevent loss of *in situ* pore fluids. Four cylindrical core plugs were cored normal to the bedding. Three cores where equilibrated for two months within desiccators with a relative humidity atmosphere of ~85%, ~75%, and ~35%, corresponding to water saturations of 70% ±10%, 58% ±10%, and 28% ±10%. The preserved core plus has an initial saturation of 92% ±10% and was stored in seawater after coring.

The equipment used for the mechanical and ultrasonic testing includes a triaxial cell, multichannel ultrasonic monitoring system, and ultrasonic *P*-wave and *S*-wave transducers (see e.g., Nadri et al. 2012). Triaxial compression tests were performed on all mudstone specimens at an effective confining pressure of 25 MPa. Different experimental protocols were used for triaxial testing of the preserved and partially-saturated core plugs. The preserved core plug was saturated with brine and the pore pressure was controlled at 2 MPa. The core plug was consolidated for six weeks until extremely low consolidation rates were reached. After consolidation, the pore pressure valves were closed (undrained conditions) and the saturated core plug was loaded axially with a constant strain rate of 10^{-7} s^{-1}. In contrast, the pore pressure was not controlled/ monitored during the compression tests of the three partially-saturated cores. The partially-saturated core plugs were consolidated for three days at isotropic stress conditions, and subsequently deformed with a constant axial displacement rate until failure.

During the experiment, ultrasonic wave velocities were measured along multiple ray paths on a single core plug to calculate the full elastic tensor, assuming a vertical transversely isotropic (VTI) elastic medium. Four *S*-wave transducers (diameter 12 mm) and sixteen *P*-wave transducers (diameter 8 mm and dominant resonant frequency ~ 0.5 MHz) were attached directly to the core plug to measure *P*-wave and *S*-wave velocities horizontally (V_{ph}, V_{sh}) and vertically (V_{pv}, V_{s1}), and the *quasi-P* wave velocity (qV_{p49}) (Figure 1). A velocity survey was performed every six hours during consolidation and every hour during axial loading. One survey consists of 18 consecutive shots fired by each transducer acting as a source. During each shot, the remaining transducers act as receivers. The average value of the measured velocities were used to obtain the full elastic tensor, hence Thomsen's elastic anisotropy parameters ε, γ, and δ (Thomsen 1986).

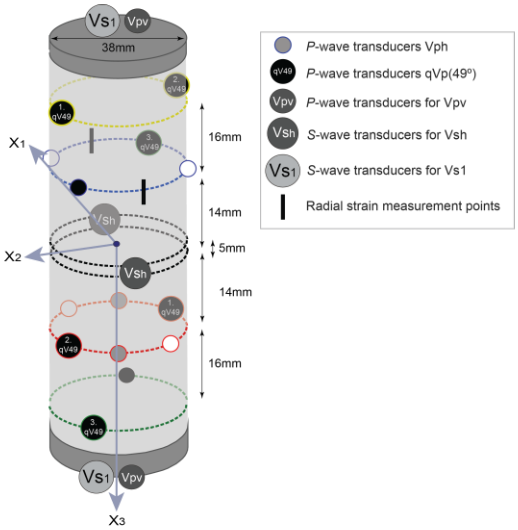

Figure 1 *Position of the P-wave and S-wave transducers on the horizontally layered, cylindrical Whitby Mudstone core plug. The measured velocities include P- and S-wave velocities (1) along the symmetry axis (V_{pv}, V_{s1}), (2) across the core diameter (V_{ph}, V_{sh}), and (3) the P-wave velocity at ~49˚ to the horizontal bedding plane (qV_{p49}).*

Results

Geomechanical properties

The degree of water saturation has a significant impact on the mechanical properties of the Whitby Mudstone. The quasi-static Young's modulus (E_3) and Poisson's ratio (υ_{31}) were obtained from the most linear part of the mean effective stress – axial strain curve. Table 1 summarises the peak strength and quasi-static elastic properties for studied mudstone core plugs with different water saturations. A decrease in water saturation increases the peak strength and stiffness (E_3) significantly. The Poisson's ratio decreases with a decreasing water saturation.

Table 1 *Mechanical properties of Whitby Mudstone core plugs with different water saturation measured during triaxial testing under a confining pressure of 25 MPa. These clay-rich rocks becomes stronger and stiffer with dehydration.*

Water saturation	*Peak Stress (MPa)*	*Young's modulus (E_3) (GPa)*	*Poisson's ratio (υ_{31}) (-)*
100%	27 ± 0.7	1.2 ± 0.2	0.36 ± 0.02
70%	41 ± 1.0	2.9 ± 0.2	0.21 ± 0.02
58%	47 ± 1.2	3.8 ± 0.2	-
28%	55 ± 1.4	4.7 ± 0.2	0.17 ± 0.01

Ultrasonic Characterisation

At isotropic stress conditions, all the *P*-wave velocities decreases with decreasing saturation (Figure 2a), resulting in a decrease of the elastic coefficients C_{11}, C_{33}, and C_{13} (Figure 2b). In contrast to the *P*-

wave velocities, S-wave velocities increase with dehydration. This increase in S-wave velocity results in an increase in shear modulus (C_{66}) (i.e., rigidity increase) (Figure 2b).

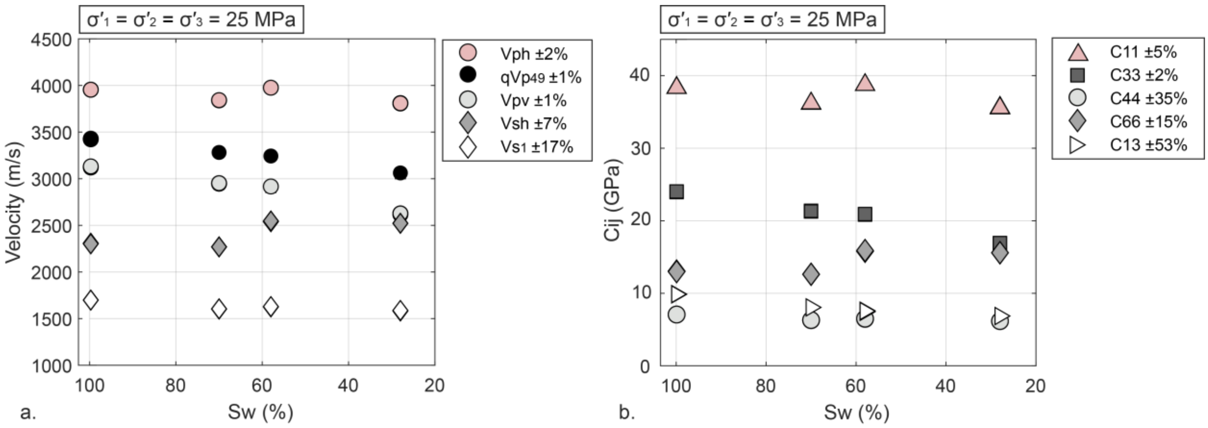

Figure 2 *a. Impact of water saturation (Sw) on the ultrasonic velocities at isotropic stress conditions. P-wave velocities decrease with decreasing water saturation, whereas S-wave velocities increase. b. The response of the elastic coefficients (Cij) to water saturation (Sw) during consolidation.* C_{33} *and* C_{66} *are the most sensitive for saturation changes.*

Elastic anisotropy

The initial *P*-wave and *S*-wave anisotropy (ε and γ) of the Whitby Mudstone is relatively high (~0.3 and ~0.4, respectively) at isotropic stress conditions (Figure 3a, b). These high anisotropy values are consistent with previous work on preserved clay-rich rocks (e.g. Dewhurst and Siggins 2006), and are caused by the presence and alignment of anisotropic clay particles, organic material, and laminations. In addition, microfractures may be present in the Whitby Mudstone core plugs due to tectonic uplift, since they originate from an outcrop. It is known that the presence of microfractures enhances the ultrasonic anisotropy (e.g., Hudson 1981; Vernik and Nur 1992).

P-wave and *S*-wave anisotropy parameters (ε and γ) increase even further (up to ~100%) with decreasing water content. The increase of ε is consistent with the findings of Yurikov et al. (2018), whereas these authors show an opposite trend for γ. This can be caused by differences in shale composition, or the absence of fractures in the Opalinus clay tested by Yurikov et al. (2018). No significant changes are observed for δ at water saturations ranging from 100% to 58%, but increases when Sw = 28% (Figure 3c). However, note that the uncertainty for δ is extremely large so the results should be treated with caution.

Conclusions

Four tests were performed on Whitby Mudstone core plugs with different water saturations. The rock strength and static elastic properties are highly affected by the degree of saturation. In addition, dehydration leads to significant changes of in the elastic anisotropy parameters. The presented results show that reporting the degree of saturation of clay-rich rocks is very important to predict there mechanical behaviour and elastic anisotropy. This needs to be considered for mechanical and geophysical interpretation for hydrocarbon exploration and production.

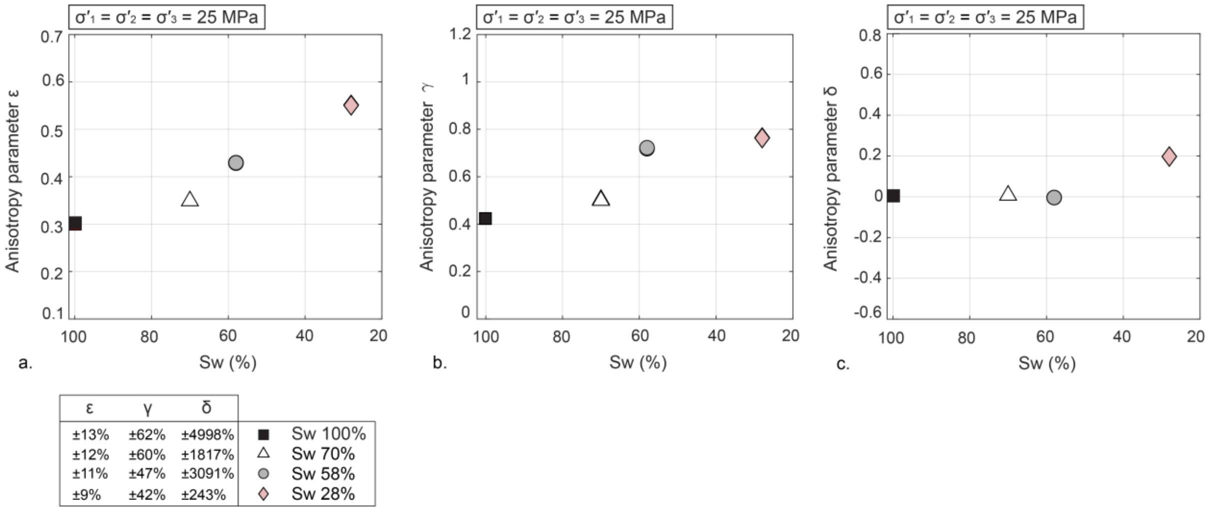

Figure 3 *Impact of water saturation on the anisotropy parameters at isotropic stress conditions. The P-wave anisotropy (ε) and S-wave anisotropy (γ) increases with dehydration (a., b.). The change in δ is less significant (c.) although the uncertainty of this parameter is high.*

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